Intact stability of passenger ships: safety issue or design concern? Neither!

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ABSTRACT

Stability has been a primary focus of the maritime industry and of immense interest to the IMO from the outset. Despite several attempts to resolve stability-related issues, the problem of stability remains one that has yet to be resolved. Reasons for this, range from the complexity of the problem itself to misconceptions in its very nature, particularly concerning intact or compromised conditions of the ship in question. Emphasis in this paper is placed on the latter. More specifically, whilst intact stability of ships is an extremely interesting scientific problem, to what extent is it a determining factor in the design and operation of passenger ships? Currently, intact stability and damage stability share the same stage from a regulatory perspective and, consequently, they have equal impact on design and operation-related decisions, an example of which is the use of combined intact and damage stability GM limit curves (e.g. IACS Rec 110 Rev1). However, in line with goal-based regulations and standards, design and operational decisions should be risk-informed in which case, matters relating to damage stability are of higher concern, simply by virtue of the fact that damage stability is by far the greater risk contributor. In fact, for passenger ships (>500GT), the level of risk associated with intact stability is indiscernible in contrast to that of damage stability. More importantly, in the operational loading conditions of such vessels, damage stability is a more dominant constraint. Hence, such ships can be designed on the basis of damage stability considerations alone. This paper delves in this direction by drawing on the current regulation-making process for risk estimation as adopted by IMO as well as current design and operational practice. Findings from European research and related studies are provided in order to substantiate the argument that intact stability for passenger ships is neither a safety issue nor a design concern.

Keywords: *Intact stability, FSA, ship safety/risk, ship design and operation*

1. INTRODUCTION

From a basic Naval Architecture perspective, concerning the design of a ship, the most fundamental objective is for the ship to remain afloat and upright, in normal operations and in emergencies, particularly flooding casualties. The relevant terms are “displacement”, relating to overall capacity at the design draft and “freeboard”, relating to the residual capacity, measured from the design draught to the freeboard deck (IMO ILLC’66). The second fundamental goal is that the ship will remain upright in the presence of external forces, even following serious loss of internal buoyancy (potentially with a list in this case). Both concepts emerged together with Naval Architecture and are as ancient as Archimedes, circa 250 BC. The topic of stability of ships (and more generally of floating bodies) has fascinated eminent scientists throughout the centuries and despite unrelenting efforts institutionally and at world scale, research remains relevant and of high focus. Stability combines deep scientific understanding with practical and ethical concerns stemming from a continually changing industry and society and, as such, it represents a prime driver for naval architects. It is not a coincidence that the form and consequences of stability regulations are at the forefront of interest at the IMO (e.g., Maritime Safety Committee and Sub-Committee on Ship Design and Construction). Many ship stability problems remain “unsolved” and the subject will remain a key focus for as long as there is human activity at sea.

From a wider perspective, maritime safety permeates all physical and temporal boundaries and, as such, is one of the most influential goals in ship design and operation. All human activity in a "risky" environment, such as the sea, is fraught with wide-ranging problems that tend to undermine safety. This is particularly true for knowledge-intensive and safety-critical ships, such as passenger ships, where the need for innovation creates unprecedented safety challenges. The Design for Safety philosophy and the ensuing formalised methodology, Risk-Based Design, was introduced in the maritime industry as late as in the mid-nineties as a design paradigm to help bestow safety as a design objective and a life-cycle imperative (Vassalos and Fan, 2016). This was meant to ensure that rendering safety a design driver would incentivise the maritime industry to seek cost-effective safety solutions, in response to rising societal expectations. In this respect, the adoption of a goal-based approach to address safety has had a profound effect, the full impact of which is yet to be delivered (IMO GBS-SLA). As a result, the subject of ship safety is one of the fastest changing topics, absorbing all forms of knowledge in the strife to respond to unrelenting societal pressure for higher safety standards and do so cost-effectively. Stability is a key focus in this quest.

However, with the focus clearly on passenger ships, certain fundamental principles have been overlooked, as a result of which all matters of stability are being pursued in the same vein, irrespective of the fact that safety implications between intact and damage stability are strikingly different. Put it differently, whilst damage stability for passenger ships constitutes the most severe safety problem, responsible for over 90% of loss of life at sea, intact stability-related loss of life, is miniscule. In fact, it is orders of magnitude lower, apart from small ships where these can be overpowered by waves, cargo shift and other excessive moments leading to capsize and potential loss of life. Usually, such ships are not involved in international trade.

Using this notion as a platform, this paper will demonstrate that loss of life (the risk) attributed to intact stability is too small to be measured for practical use. The basis for this is the IMO-established methodology for risk estimation of a given hazard in support of the regulation-making process i.e., the Formal Safety Assessment (FSA). In this respect, evidence will be presented to substantiate this claim in support of the argument that intact stability is not a safety issue for passenger ships. Industry has realised this many years ago and took action by: (a) increasing GM 3-fold to avoid dynamic stability problems (e.g., parametric roll, dead-ship condition) and (b) installing sophisticated motion stabilisers to ensure reduced motions and accelerations as well as provide maximum comfort in all operating conditions.

Having said this, with focus on damage stability considerations, innovative solutions will be identified, which with time, could potentially render damage stability an equitable risk contributor to intact stability (Vassalos, et al, 2019). Risk balance will then become a key design concern in which case both intact and damage stability will be deserve due attention.

Intact stability is not a design concern! This sounds even more precarious than intact stability not being a safety issue. However, evidence presented in the paper demonstrates that within the operational range of passenger ships (cruise ships and RoPax), ship design and operation are governed by damage stability considerations. This is unsurprising, as it is the case for other safety-critical ship types such as surface combatants.

Realising this, will not change current design practice substantially (in terms of substituting one limiting curve with another or continue using the 2nd Generation Intact Stability criteria as guidelines, currently under consideration at IMO (SDC 6/5, 2019), but will help the profession to focus, identify and resolve damage stability issues as primary concern, thus investing cost-effectively to improve maritime safety. In addition, operational data for these ships will be used to show that, in the range of drafts where passenger ships normally operate, stability requirements are dictated by damage stability considerations. Stemming from the above, specific conclusions are drawn.

2. FORMAL SAFETY ASSESSMENT

With the advent of goal-based standards, risk-based approaches and regulations have been introduced in the maritime industry to guide ship design and operation. However, whilst such approaches address by definition the life cycle of the ship, the focus of the regulations remains design-biased.

Risk-based ship design introduces risk analysis and evaluation into the traditional design process with the ultimate aim of meeting safety objectives cost-effectively. Risk, in this respect, is a metric for quantifying safety performance. With safety treated as a measurable objective, design optimisation can effectively be expanded and the new objective to minimise risk can be addressed alongside other traditional design objectives relating to earning potential, speed, cargo carrying capacity, etc., (Sames, 2007). One of the main outputs relates to "balanced" decision-making concerning risk, cost and performance on the basis of risk evaluation thresholds.

The vehicle for this in the maritime industry is IMO, concerning regulatory developments and amendments. One instrument that is fundamentally risk-centric is the Formal Safety Assessment (FSA) process, which was introduced by the IMO as a direct response to the explosion of the Piper Alpha offshore platform in the North Sea, where 167 people lost their lives. The first integration of FSA in the regulation-making process took place in 2002, by the approval of relevant guidelines laid out in MSC/Circ. 1023 - MEPC/Circ. 392 (IMO, 2002). Recently, the FSA guidelines have been revised twice by MSC/Circ.1180 - MEPC/Circ.474 (IMO, 2005) superseded by MSC-MEPC.2/Circ.5. (IMO, 2018). The FSA is a rational, holistic and systematic process for assessing risks relating to maritime safety, the protection of the marine environment, and for evaluating costs and benefits of various options to reduce these risks (IMO, 2015). Notably, the use of FSA is consistent with, and will provide support to, the IMO decision-making process, leading to international legislation for rendering pertinent risks As Low As Reasonably Practicable (ALARP). The FSA includes a number of generic, logically arranged steps as indicated in Figure 1, which reflect different stages of resolving a safety issue.

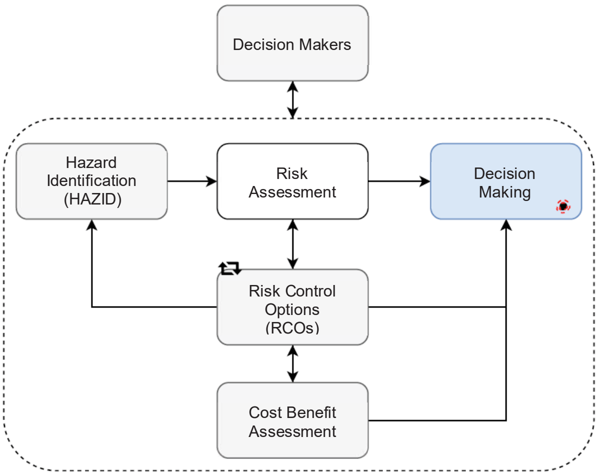

Figure 1: Process of Formal Safety Assessment (FSA)

In the era in which the maritime community changes direction from a reactive to a proactive safety approach, the Formal Safety Assessment provides the right vehicle for risk-informed legislation and general decision making.

Relating to the problem at hand, the European project (SAFEDOR, 2005-2009) performed Formal Safety Assessments for both RoPax and Cruise Ships with the view to quantifying related risks during the life-cycle. Table 1 next, summarises the results of the FSAs.

As one could readily observe, intact stability is absent from the potential risk contributors, not because it was omitted from the analysis but because the contribution to risk from intact stability concerns is negligible. Despite the fact that loss includes consequences of heavy seas and tropical rain, large ship motions and impact of water ingress into the cargo hold, the risk remains negligible.

In the case of RoPax ships, the FSA includes accidents from 1994 to 2004 (IMO, 2008b) and for cruise ships from 1990 to 2004 (IMO, 2008a). Even though, the risk for collisions, grounding and contact/impact is very high, water ingress due to damage has been investigated separately for the case of RoPax vessels. The results indicate a PLL (Potential Loss of Life) due to flooding as high as 1.12E-1 per ship-year.

Table 1: FSA findings for Passenger ships derived from project SAFEDOR. Indication of frequency and Potential Loss of Life per ship year.

	Type	Frequency (per ship year)	PLL (per ship year)
RoPax	Collision	1.25E-02	2.34E-02
	Grounding	9.57E-03	2.57E-02
	Impact	1.25E-02	1.39E-03
	Flooding	2.39E-03	1.12E-01
	Fire	8.28E-03	5.95E-02
	Total	**4.52E-02**	**2.22E-01**
Cruise Ships	Collision	4.60E-03	2.40E-01
	Contact	1.20E-03	9.20E-03
	Grounding	9.80E-03	1.50E-01
	Fire/Explosion	8.90E-03	1.50E-02
	Others	2.00E-02	6.40E-03
	Total	**4.45E-02**	**4.21E-01**

3. SAFEDOR CASE STUDY

In the European project (SAFEDOR, 2005-2009), (Themelis et al., 2007) presented a novel method of probabilistic assessment for intact stability, applicable to different ship types. One of the ship types considered is a RoPax ferry, which aided in identifying the fraction of risk for different problems related to intact stability.

The approach was tailored for a specific ship, assessing three failure modes, namely: beam-sea resonance, parametric rolling and pure loss of stability for specific routes in Mediterranean Sea. The methodology entailed identification of critical wave groups that give rise to dynamic responses exceeding a threshold, which is established based on the probability of encountering pertinent critical wave groups for the areas under consideration. The assessment of the intact stability-related failure modes or else “instability” is based on the development of wave environment thresholds. The developed failure norms address distinctively the safety of the ship. For the RoPax vessel, this norm is expressed through a critical angle of roll.

The results of the study are provided in Table 2. In particular, the findings of the analysis indicate very low probability of instability when mean seasonal values (even for winter) are considered. This is the case for the marginal probabilities of Hs and Tz, accordingly. From an operational perspective, in order to account for actual cases, the joint probability of encountering Hs and Tz is considered (Themelis and Spyrou, 2007), as shown in the table below, in which the values refer to the entire voyage time.

Table 2: Probabilities for ROPAX (Themelis and Spyrou, 2007)

	Total probability	Critical time ratio
Beam-sea resonance Ship (φ>35°)	1.88E-16	2.74E-16
Parametric rolling Ship (φ>35°)	4.99E-28	9.64E-28
Pure loss of stability Ship (φ>35°)	6.49E-19	1.86E-19

In simple terms, indicative values for intact-stability-related risk are miniscule on the basis of such low frequencies of encountering critical wave conditions, even assuming conservatively that such encounters will lead to life loss.

According to the authors (Themelis and Spyrou, 2007): “These probabilities represent the number of critical waves over the total number of encountered waves. With this in mind, considering a ship lifetime of 25 years, half of which at sea and a mean wave period of 8 seconds, for a year of continuous vessel operation (60 x 60 x 24 x 365/8), 25 years of the ship lifetime produces 10^8 waves per ship”. This means that a fleet of 5E20 needs to operate continuously for 25 years in order to have 1 parametric roll according to the low probabilities shown in Table 2. However, it will be of interest to undertake a complete study aimed at clarifying this issue as a general concern.

4. LIMITING GM CURVES

Design Condition

Currently, intact and damage stability considerations and ensuing requirements are expressed in the form of limiting GM curves for intact and damage stability, both presented without any due consideration of the risk associated with each condition. This leads to the same emphasis being placed for intact and damage stability requirements and this, in turn, may lead to sub-optimal designs. More specifically, for passenger ships, the risk due to damage stability is orders of magnitude higher than that pertaining to intact stability and this information is not being reflected through the limiting curves, thus not being properly accounted for in the design process and during operation.

Damage stability is assessed for thousands of damage cases and potential scenarios, in three loading conditions (dl, dp, ds), using the Attained Index as a means of statutory compliance. On this basis, the Limiting GM curves are derived following compliance of each draft with the inequality A≥0.9R for passenger ships. This way, risk (for example, Potential Loss of Life – PLL) is calculable and reflects all requisite knowledge. For intact stability, on the other hand, to date, the limiting curve is derived following compliance with the severe wind and rolling criterion for different KGs, indicating the ability of a vessel to withstand the combined effects of beam wind and rolling in a scenario that bears little or no relation to reality. Second generation intact stability criteria address more realistically intact-stability related concerns, including potential problems but risk estimation remains characteristically absent. This being the case, the ensuing results lack risk content and information. Therefore, from a risk-based perspective, any deduction on risk pertaining to intact and damage stability and comparison between the two, could be misleading. In the face of this, ships may be sub-optimally designed.

On the other hand, the limiting GM curve linked to intact stability provides implicit information on the payload as a function of draft and KG. This, in turn, allows designers at the early stages of design to make decisions concerning global ship parameters and loading conditions. Accounting for this, it will be of interest to examine if passenger ships could be designed from damage stability considerations alone.

Pertaining to the above, Figure 2 and Figure 3 below indicate the limiting GM curves for intact and intact stability relating to medium/large passenger ships (cruise ship and RoPax). Three points are noteworthy:

(a) ships are designed with a large GM margin for better life-cycle stability management
(b) the damage stability limiting GM is dominant, particularly at the design draft (5.35m for RoPax and 8.75m for the cruise ship)
(c) The gap between intact and damage stability requirements widens with increasing drafts.

Related to this, previous studies from (Paterson et al., 2018) have demonstrated that passenger ships operate at the upper region of their draft distribution when actual operational profiles are considered. More specifically, almost 75% of the loading conditions operate at drafts higher than the SOLAS damage stability partial draft.

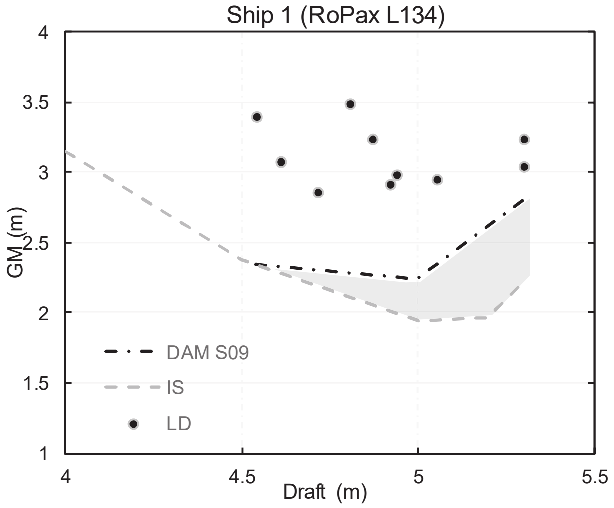

Figure 2: Intact and damage limiting GM curves along with design loading conditions for a medium size RoPax

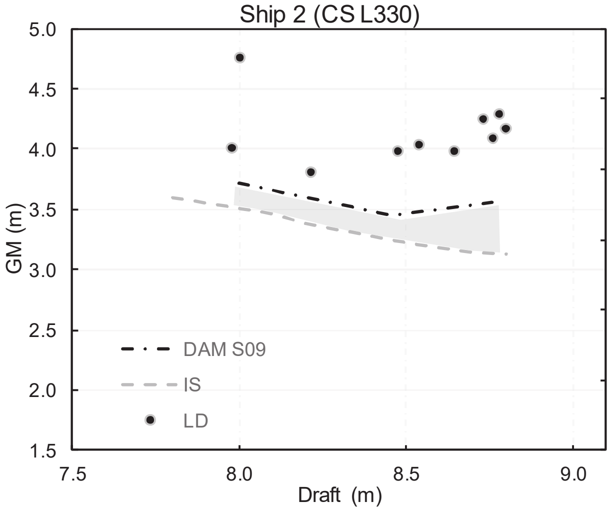

Figure 3: Intact and damage limiting GM curves along with design loading conditions for a large cruise ship

These limits, as described above, are meant to provide for safe operation and, as such, there is a link to risk. Attempting to calculate this for both intact and damage stability is not straightforward and hence a heuristic approach is utilised herewith, based on frequency estimation of pertinent events. This is used as a metric for Potential Loss of Life (fatalities) as a function of the People On Board (POB). This is shown in Figure 4 for the RoPax and cruise ship referred to earlier.

This way, for intact stability, incident-specific frequency per ship year is used incorporating all three potential modes of loss as provided in Table 2. For damage stability, pertinent results for this ship are given in the EMSA III Project (EMSA, 2013).

Figure 4 shows the difference between intact and damage stability-related risk (PLL), which spans orders of magnitude. The difference between RoPax and Cruise ship stems merely from the difference in size and passenger capacity. Following this process of assigning risk content in the intact stability limiting curve, leads to uncharacteristically low intact stability limiting GMs. As a result, it would not be sensible to consider intact and damage stability limits together, a point made frequently in the past.

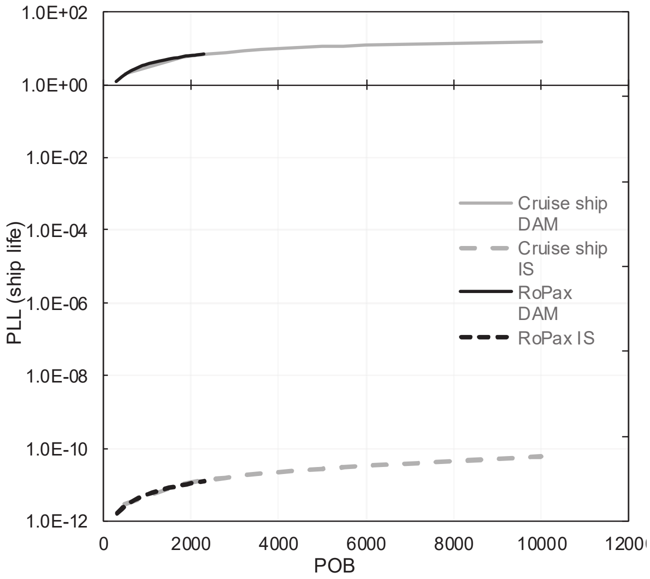

Figure 4: Potential Loss of Life per ship life for one cruise ships and one RoPax for intact and damage stability respectively

Operational condition

In the operational stage of the life-cycle of passenger ships, vessels tend to operate at the upper envelope between the partial and deepest damage stability drafts, as mentioned in the foregoing. This is demonstrated in Figure 5 and Figure 6 for RoPax and Cruise ship, respectively. The graphs show that all operational conditions are governed by damage stability requirements for the related operational range.

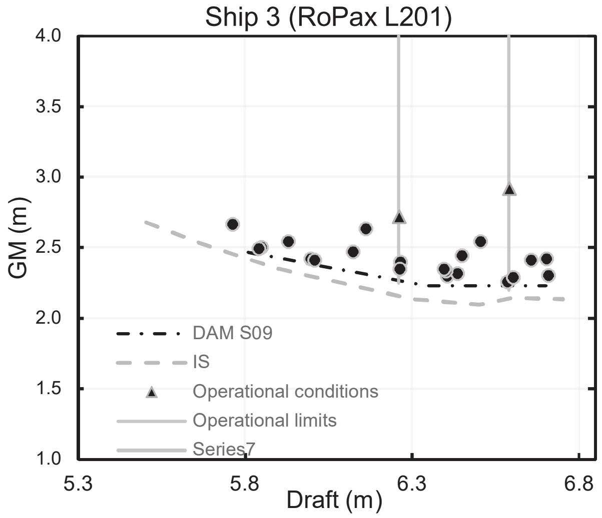

Figure 5: Operational and design conditions along with damage and intact damage limiting GM curves for a large RoPax

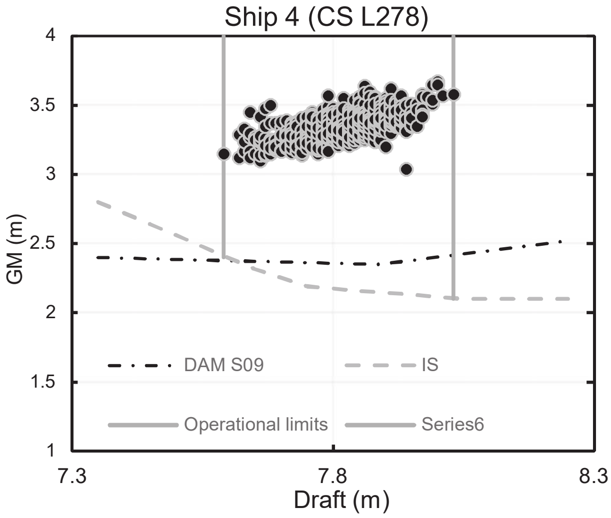

Figure 6*:* Operational conditions, damage and intact damage limiting GM curves for a large cruise ship

5. CONCLUSIONS

Based on the information and arguments presented in the foregoing, the following conclusions nay be drawn:

- For passenger ships (>500GT), the level of risk associated with intact stability is indiscernible in contrast to that of damage stability.

- Given that design and operational decisions should be risk informed, matters relating to damage stability should be given priority. In this respect, recently agreed 2nd Generation Intact

Stability Recommendations will serve a useful purpose.

- However, given that in the operational draft range of passenger ships damage stability considerations are dominant, ships could be designed on the basis of damage stability considerations alone, in that this indirectly caters for intact stability requirements.

6. REFERENCES

IMO 2008a. MSC 85/17/1 Formal Safety Assessment (FSA) cruise ships. London.

IMO 2008b. MSC 85/17/2, Formal Safety Assessment (FSA) RoPax ships. London.

IMO 2015. Revised Guidelines for Formal Safety Assessment (FSA) for Use in The IMO Rule - Making Process. In: IMO (ed.). London.

Vassalos, D, Patterson, D. & Boulougouris, E. Flooding Containment System, MT Journal, 2019.

Paterson, D., Vassalos, D., Atzampos, G., Boulougouris, E., Cichowicz, J. & Luhmann, H. Rebooting SOLAS - Impact of drafts on damage survivability of cruise ships. Proceedings of the 13th International Conference on the Stability of Ships and Ocean Vehicles, STA2018, 2018 Kobe, Japan.

SAFEDOR 2005-2009. Design, Operation and Regulation for Safety, EU project, FP6-516278.

Sames, P. Risk-Based Frameworks for ship designa and approval. 10th Int. Symposium on Practical Design of Ships and other Floating Structures, PRADS, 2007 Houston.

Themelis, N. & Spyrou, K. Probabilistic assessmemt of ship stability. Transactions - Society of Naval Architects and Marine Engineers, 2007 SNAME. 181-206.

Themelis, N., Spyrou, K. & Niotis, S. 2007. SAFEDOR-D-2.3.6-2007-06-15-NTUA–rev-1, Implementation and application of probabilistic procedures In: NTUA (ed.). Athens.

Vassalos, D., Atzampos, G., Cichowicz, J., Paterson, D., Karolius, K., Boulougouris, E., Svensen, T., Douglas, K. & Luhmann, H. Life-cycle flooding risk management of passenger ships. Proceedings of the 13th International conference on the stability of ships amd ocean vehicles, STAB, 2018 Kobe, Japan.

Vassalos, D. & Fan, M. Risk-Based design - Realising the triple-a navy. 13th International Naval Engineering Conference and Exhibition (INEC 2016), 2016 Bristol.

EMSA, 2013. Risk acceptance criteria and risk based damage stability, Final report, part 2: Formal Safety Assessment (EMSA/OP/10/2013).